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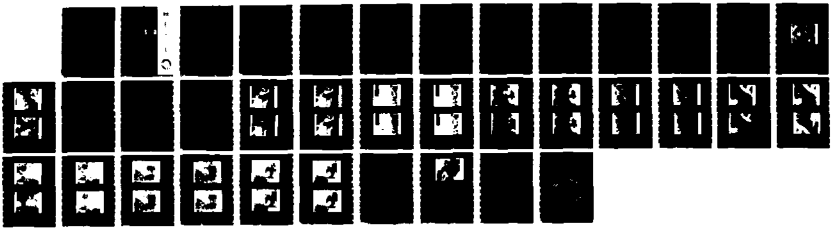

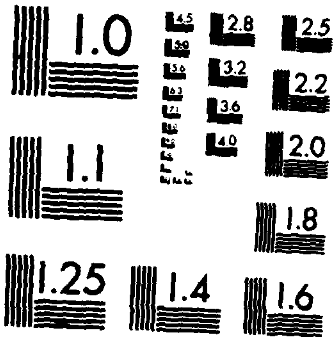

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Sparse area stereo matching experiment

Michael A. Crombie

July 1986

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The algorithm used in this experiment is considered by many to be state-of-the-art for calculating x-parallax over rural regions. Even so, its output must be refined in sparse areas in order to meet accuracy requirements. The major result of this experiment showed that x-parallax should be measured from digital imagery containing no more than 10 line pairs per millimeter.

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PREFACE

This study was conducted under DA Project 4A762707A855, "Topographic Mapping Technology."

The study was done during 1984 under the supervision of Mr. Dale E. Howell, Chief, Information Sciences Division, and Mr. Lawrence A. Gambino, Director, Computer Sciences Laboratory.

COL Alan L. Laubscher, CE was Commander and Director and Mr. Walter E. Boge was Technical Director of the Engineer Topographic Laboratories during the report preparation.

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INTRODUCTION

The mapping community has for the most part addressed the problem of automatically extracting (MC&G) features from digital images by concentrating on one kind of feature, while ignoring relationships with other features. The various tasks are performed using algorithms that are basically mathematical rather than cartographical. In some cases pattern recognition algorithms are used to extract several features in one computer pass where, generally, unknown a priori probabilities could be imposed before the fact and relaxation methods after the fact to enforce relationships among the features. In any case, the results to date vary from resounding failures to partial successes.

There are several reasons for the highly mathematical cast to the pertinent algorithms. Many of the algorithms were developed previously by mathematicians (e.g., pattern recognition) for a variety of signal processing problems other than for picture processing. Many texture algorithms were developed recently by electrical engineers where computer compatibility (polynomials, separable window functions, etc.) may have had as much influence on the algorithm development as concepts of image texture. Almost all of the image– processing algorithms were designed with an ideal image in mind rather than the cluttered aerial image we must deal with. Most of the algorithms seem reasonable at first sight, yet all turn out to be *ad hoc*.

One of the basic assertions proposed by the U.S. Army Engineer Topographic Laboratories (ETL), the Computer Sciences Laboratory (CSL) is that our understanding of the imaging event with respect to the extraction of useful MC&G detail is insufficient for purely algorithmic development. In practical terms it is asserted that there exists only a limited understanding of the relationship between image detail and real world detail at the grey shade level. Real world constraints in the form of physical laws and II (image interpreter) knowledge must in some manner be imposed on the feature extraction process if the output from the several front–end processors (mathematical algorithms) is to be improved. This, we assert, can be done at the next step above the grey shade level, i.e., at the output of the front–end processors. Each of the several front–end processors are producing preliminary estimates of a peice of information about the terrain. These data can be related by knowledge and by physical laws to reinforce one another and can even be used to derive information of a higher level that no processor could do alone.

The overall feature extraction process should run smoother if the individual front–end processors produce as much error free feature estimates as possible. A front–end processor[1] designed to estimate X–parallax information over rural regions from a stereo

[1] F. Raye Norvelle. *Interactive Digital Correlation Techniques for Automatic Compilation of Elevation Data*. U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL–0272, October 1981, AD–A109 145.

pair of aerial images is the subject of this Research Note. The purpose of the work is to find ways to use the existing front–end processor in such a way that its output will bear up under the scrutiny of other information estimates derived from other processors. Note that the core algorithm in the X–parallax front–end processor is based on the simple notion of template matching. The algorithm in no way reflects the accumulated lore of the Image Interpreter nor his synoptic view of the stereo scene when he removes X–parallax. Some of the accumulated lore and certainly some of the synoptic view may be enforced when other front–end processor outputs are considered in a cooperative manner along with the X–parallax output.

BACKGROUND

One major aspect of feature extraction is the automated extraction of X–parallax data from digital stereo images for subsequent Digital Terrain Matrix (DTM) development. Several studies were conducted in–house to determine the best measure of similarity for mapping on the fly over rural areas and the results indicate that the linear correlation coefficient of statistics is the best. This measure may be postulated from statistical considerations or else deduced from the simple notion of template matching. A major finding associated with our in–house efforts and evaluated in this study was that most of the useful parallax information can be obtained from image resolution ranging from 1 to 10 line pairs per millimeter.[2]

A salient feature of our approach to the determination of X–parallax, as it evolved at ETL, CSL, is to operate entirely in image space. There are several reasons for this approach, not the least of which is that a variety of images can be processed over the same area without exact knowledge of their exterior orientation. Sufficient exterior orientation data must be available so that most of the Y–parallax between stereo pairs can be removed by a reformatting exercise. Another important feature of our approach to X–parallax determination is that one digital image over a particular area is regarded as the master image, whereupon a rectangular grid of line and sample coordinates are designated for X–parallax determinations. This approach reduces computation time for image shaping, provides for image to image mapping for other purposes, and most of all, provides a defined image space data base framework for subsequent coordination of other real world feature estimates. This approach was enlarged upon and reported to the scientific community in April 1983, at the ASP convention in St. Louis, Missouri.[3]

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[2]M. Crombie, and R. Rand. *An Evaluation of the Method of Determining Parallax From Measured Phase Differences*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL–0145, December 1977, AD–A056 006.

[3]M. Crombie. *Coordination of Stereo Image Registration and Pixel Classification*, Photogrammetric Engineering and Remote Sensing, Vol.49, No. 4, April 1983.

Three test programs were developed over the course of the investigations. The first program was a batch program developed on the CDC 6600 at the Belvoir Research and Development Center (BRDC).[4] The second program was another batch program developed on the CDC 6400 at ETL, CSL[5] which used findings from the first effort and provided a basis for the third program.[6] The third program seems to provide the state-of-the-art with respect to techniques in stand-alone X-parallax extraction over rural areas. The program is a Digital Image Analysis Laboratory (DIAL) program that will allow for a large variety of test procedures, many kinds of parametric tweaking, and most importantly, interactive control. The program was adjudged comprehensive enough to install on the Remote Work Processing Facility (RWPF) at the two Defense Mapping Agency (DMA) production centers.

Another test associated with the overall effort and which has some bearing on this study was a relaxation experiment designed to remove elevation errors.[7] In that experiment the relaxation algorithm was applied to the results from the second compilation test program in order to remove several very noticeable errors in the derived DTM. The resulting improvement was displayed both as a grey shade relief image and as a contour map and compared to the same output derived from the third compilation test program. Isolated errors were removed, but errors over an extended area were not. It was determined in that study that a better match process must be developed over regions of sparse detail and that a basic law of data processing, namely "garbage in – garbage out," must not be ignored.

NUMERICAL EXPERIMENT

The objective of this report is to find ways to improve the output of the X-parallax front-end processor without using information from other front-end processors, and without drastically revising the algorithm. Two approaches were tested, namely to provide to the processor image data most suitable for rural type matching and to use similar yet less demanding procedures in difficult areas. In the first case, stereo matching was

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[4] P. Rosenberg, E. Erickson, and G. Rowe. *Digital Mapping System: Mathematical Processing*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL-CR-74-6, May 1974, AD 782 230.

[5] M. Crombie. *Stereo Analysis of a Specific Digital Model Sampled From Aerial Imagery*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL-0072, September 1976, AD-A033 567.

[6] F. Raye Norvelle. *Interactive Digital Correlation Techniques for Automatic Compilation of Elevation Data*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL-0272, October 1981, AD-A109 145.

[7] M. Crombie and J. Shine. *An Analysis for a Relaxation Scheme to Improve Terrain Elevation Data*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL-0298, July 1982, AD-A119 257.

performed with digital pictures containing up to 10 lp/mm of information, and in the second case large correlation windows were used on difficult points. The latter approach was performed with another DIAL program designed to measure corresponding points in a pass point mode. It should be noted that this program was also considered relevant to expected DMA experiments and was installed on the RWPF.

The first approach was conducted in conjunction with an experiment in road following.[8] This experiment, which is just starting, is the first attempt to coordinate output from two front–end processors for the mutual benefit of each. The second experiment was conducted using a subregion of the stereo model used in the first experiment, where the image information content was 20 lp/mm.

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[8] J. Brown. *Coordination of Effort to Include AI Techniques Into a Line Follower Program*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va.,−−In print.

10 lp/mm Results. The primary purpose of this experiment is to develop a DTM so that terrain slope information could be used in a rule–based regimen to better define the path of roads and especially the paths of creeks. The scene is depicted in figure 1. Note that the picture is a four time reduction of the digital scene and was photographed from a TV display. The original digital scene is a 2048 by 2048 by 8 picture with 50μm lines and sample spacings. The original hardcopy scale was approximately 1:70,000, and X–parallax was measured automatically over a grid defined by a 5–pixel spacing and a 5–line spacing. Thus, the output spacing was about 57.4 feet over a region 4.45 by 4.45 miles square.

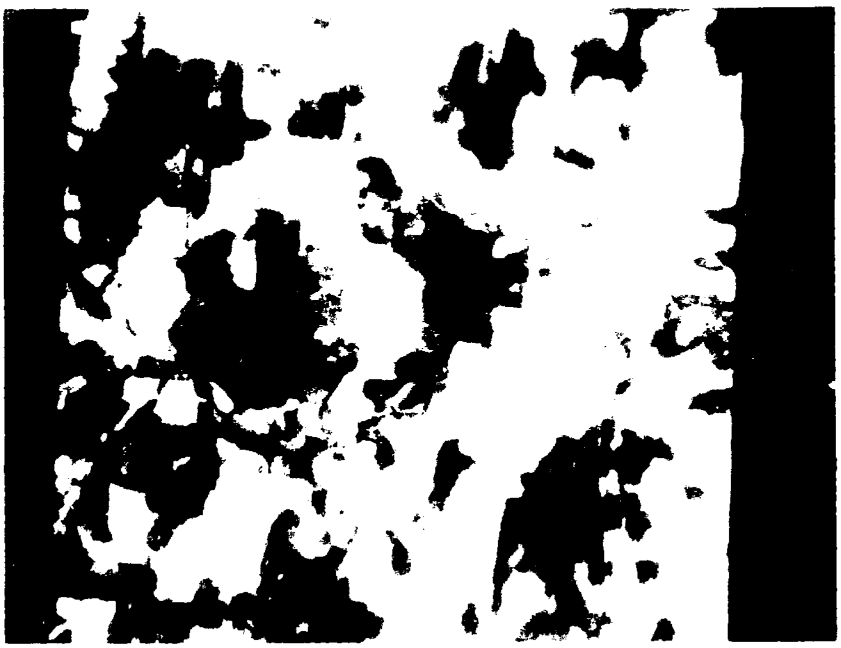

Figure 1. 10 lp/mm full scene

Approximately 1 percent of the points were rejected by the automatic front–end processor. Figure 2 depicts block 7 (one of the 16 equally sized blocks over figure 1). Figure 3 depicts block 8. The white dots repesent points rejected by the front–end processor. Compare these results with figures 5, 9, 13; and 17 for block 7; and with figures 21, 25, 29;, and 33 for block 8 where the same processor rejected points over the same area but from digital pictures with up to 20 lp/mm, and where the experiment was performed by a different operator.

Figure 2. Block 7 rejects

Figure 3. Block 8 rejects

20 lp/mm Results. The primary purpose of this experiment is to get some idea about how well the same front–end processor used in the 10 lp/mm experiment would measure X–parallax when the input data contained up to 20 lp/mm. The result was that approximately 10 percent of the matches were rejected by the processor. Figures 4, 8, 12 and 16 are subscenes pertaining to block 7; figures 20, 24, 28 and 32 pertain to block 8. The line and sample spacings of each of these 512 by 512 by 8 scenes is 25μm. The X–parallax was measured automatically over a grid defined by a 10–pixel spacing and a 10–line spacing, which corresponds to a 57.4 foot ground spacing.

Visual displays of the mismatched points (white dots) are shown on figures 5, 9, 13 and 17 for block 7; and on figures 21, 25, 29 and 33 for block 8. A numerical presentation of the process history for each of the 8 subscenes is given in tables 1 and 2. Note that the processor will make up to four attempts to develop a successful match. A successful match is declared when a function of the correlation value, estimated X–parallax, signal power on the master image, and correlation function shape satisfies a specified threshold.

Table 1. Record of good and bad matches for 20 lp/mm

Scene	Number Of Points Attempted	Match Attempt 1	2	3	4	Good	Bad
7-A	2068	1330	74	77	322	1803	265
7-B	2160	1946	46	26	51	2069	91
7-C	2064	1079	73	66	447	1665	399
7-D	2019	1384	58	41	186	1669	350
8-A	1968	1453	69	54	273	1849	119
8-B	1974	1402	87	63	288	1840	134
8-C	2112	1428	80	65	294	1867	245
8-D	2115	1440	73	65	355	1933	182

The processor, upon request, will produce summaries of data relevant to the image and to the process. Of the points that were adjudged successful after the first attempt, those that passed because of a good correlation (RXY), an acceptable X–parallax (DX), and others are listed. The average correlation of acceptable matches and the average correlation of unacceptable matches are listed. The same is true for X–parallax and signal power. The signal power pertains to the window of data on the master picture.

Table 2. Processing summaries for 20 lp/mm

				Average RXY		Average ¶DX¶		Average Signal Power	
Scene	Good RXY	Good DX	Other	Good	Bad	Good	Bad	Good	Bad
7-A	369	83	21	.523	.275	.82	2.64	597	289
7-B	91	21	11	.572	.335	.74	2.77	762	404
7-C	453	126	7	.518	.248	.78	2.33	467	225
7-D	219	60	6	.532	.212	.63	2.64	502	250
8-A	358	38	0	.559	.272	.64	1.95	655	310
8-B	376	54	8	.518	.281	.77	2.74	655	376
8-C	358	72	9	.542	.285	.77	2.31	610	296
8-D	424	61	8	.531	.255	.73	2.29	615	303

An attempt to rematch the rejected points with a pass point program was tried next. In that program, the two scenes are blurred by a resampling exercise where the 512 by 512 by 8 images are replaced with 64 by 64 by 8 images. An attempt is made to match the blurred pixel value on the master (i.e., that pixel which was derived from the 8 by 8 by 8 subimage of the original containing the point in question), to its corresponding point on the slave image. If the match is successful, a point near the center of the 8 by 8 by 8 subimage on the slave is used as a first estimate in subsequent full resolution matches. An iterative process begins by developing a match point on the slave image using 7 by 7 correlation windows. Then, if the match point developed on the slave image using a 9 by 9 window is within 1/2 pixel of the 7 by 7 result (both in X−parallax and in Y−parallax corrections), the process halts and declares the 9 by 9 result as the match. Otherwise, the process proceeds with a 11 by 11 window using the 9 by 9 result as an estimate. Again, if the two results are within 1/2 pixel the process halts and declares the 11 by 11 result as the matchpoint. The process will repeat until the window size is 31; failure at this point is designated as a process failure to converge and the exercise is halted. The process will also halt if any of the windows go beyond the digital image boundary. Visual displays of those points that were rejected by the original processor and also rejected by the pass point processor are shown in figures 6, 10, 14 and 18 for block 7; and in figures 22, 26, 30 and 34 for block 8. A numerical summary of the results is given in table 3.

Table 3. Record of rejected points in the pass point computation

Scene	Rejects	Y – parallax	Lack of Convergence	Edge Problems
7-A	80	48	32	0
7-B	18	10	4	4
7-C	127	72	47	8
7-D	94	27	16	51
8-A	45	26	15	4
8-B	33	19	13	1
8-C	84	28	27	29
8-D	76	25	10	41

Exact Y–parallax was determined by an intersection exercise where if the total Y–parallax exceeded 80 m (a little more than 3 line spacings), then the point was rejected. The intersection was carried out using known exterior orientation data. Note that Y–parallax can be controlled exactly when the relative orientation of the two exposures is known and especially when, as in our case, all match point errors can be attributed to the slave image.

Since Y–parallax can be controlled to within accuracy limits defined by the exterior orientation data and since the edge problem rejections have to do with format rather than with procedure, the errors of interest here are those caused by a lack of convergence. A visual display of those points that were rejected by the original processor and also rejected by the pass point processor for failure to converge is shown in figures 7, 11, 15 and 19 for block 7, and in figures 23, 27, 31 and 35 for block 8.

Figure 4. Scene A of block 7

Figure 5. Scene A of block 7—rejects

Figure 6. Scene A of block 7 – pass point rejects

Figure 7. Scene A of block 7 – pass point convergence failure

Figure 8. Scene B of block 7

Figure 9. Scene B of block 7—rejects

Figure 10. Scene B of block 7—pass point rejects

Figure 11. Scene B of block 7—pass point convergence failure

Figure 12. Scene C of block 7

Figure 13. Scene C of block 7 – rejects

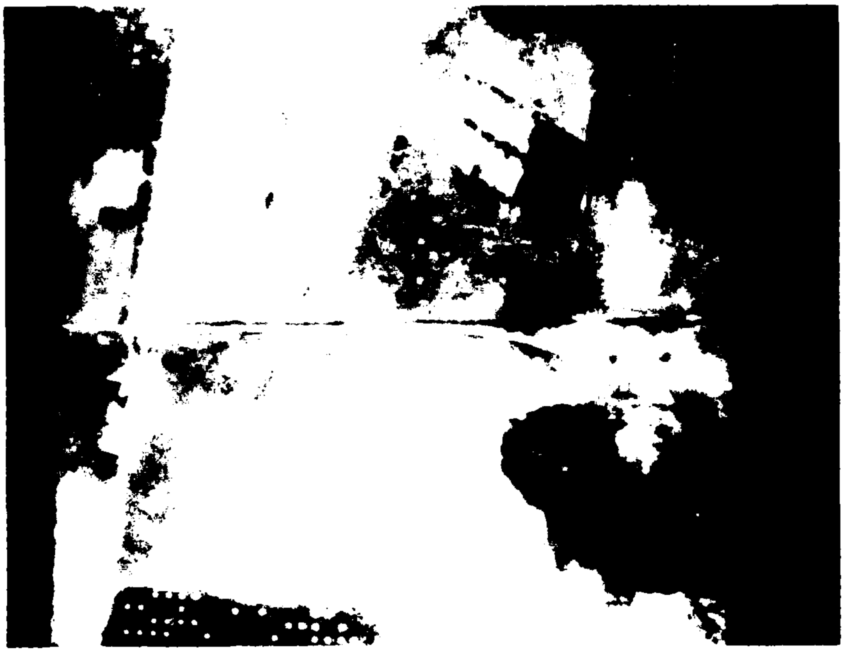

Figure 14. Scene C of block 7 – pass point rejects

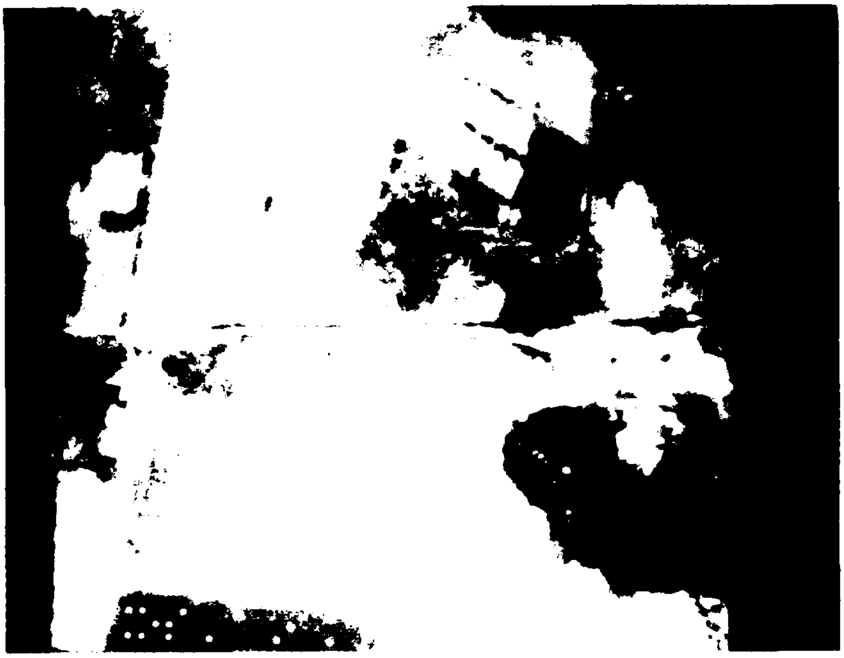

Figure 15. Scene C of block 7 – pass point convergence failure

Figure 16. Scene D of block 7

Figure 17. Scene D of block 7 - rejects

Figure 18. Scene D of block 7—pass point rejects

Figure 19. Scene D of block 7—pass point convergence failures

Figure 20. Scene A of block 8

Figure 21. Scene A of block 8 – rejects

Figure 22. Scene A of block 8—pass point rejects

Figure 23. Scene A of block 8—pass point convergence failure

Figure 24. Scene B of block 8

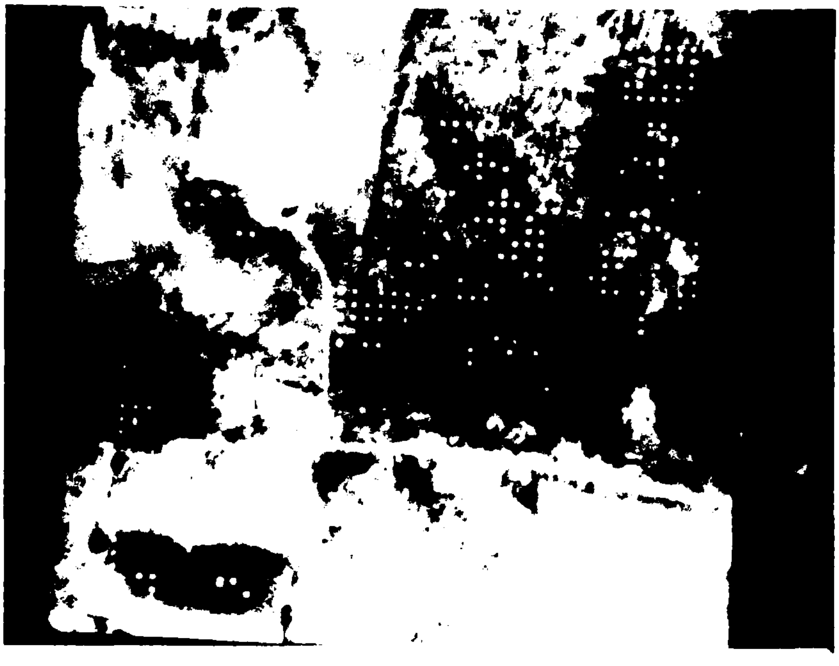

Figure 25. Scene B of block 8 – rejects

Figure 26. Scene B of block 8—pass point rejects

Figure 27. Scene B of block 8—pass point convergence failure

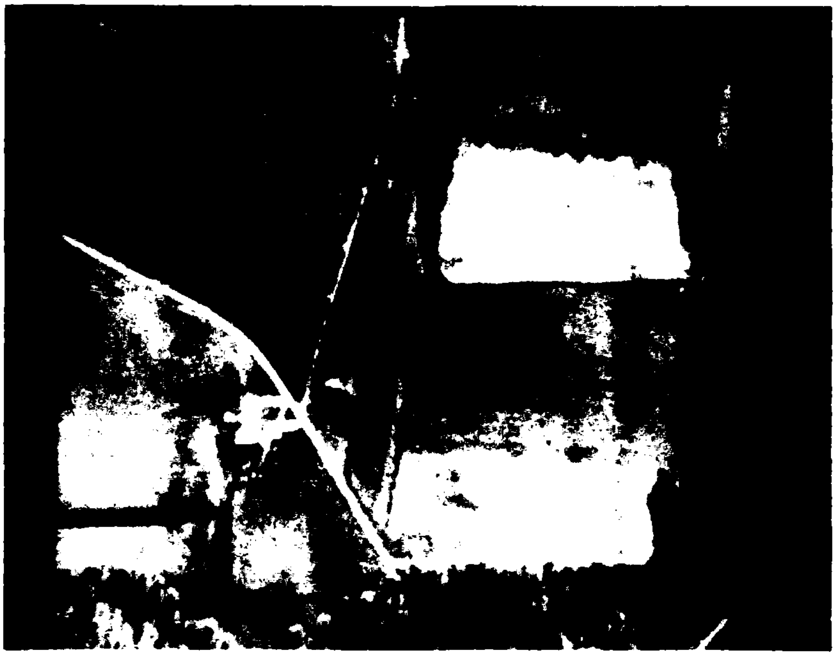

Figure 28. Scene C of block 8

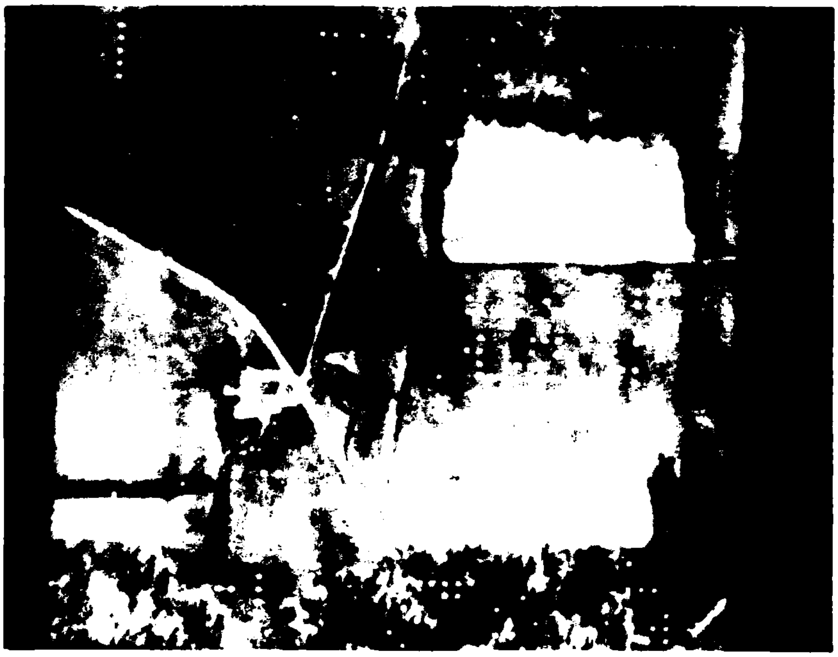

Figure 29. Scene C of block 8—rejects

Figure 30. Scene C of block 8—pass point rejects

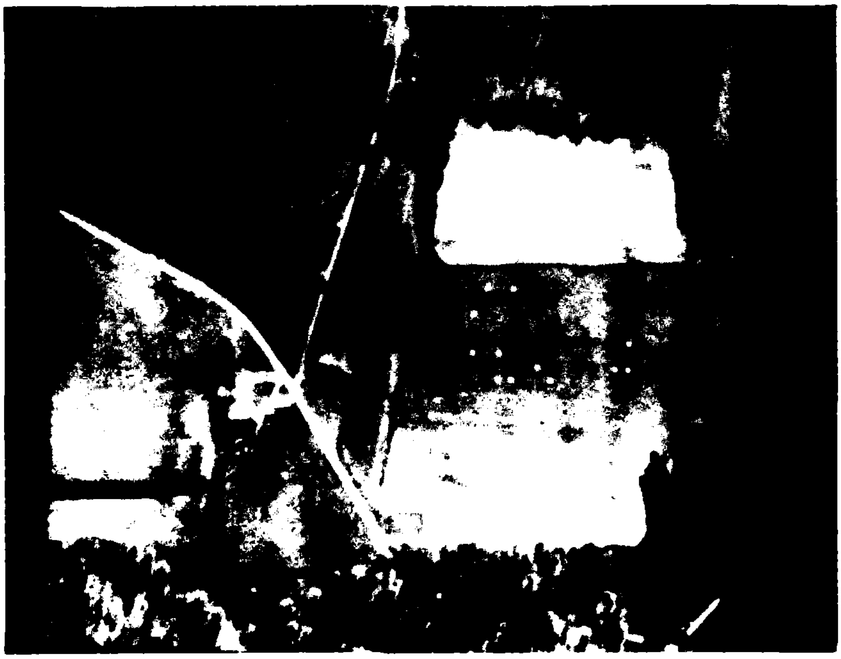

Figure 31. Scene C of block 8—pass point convergence failure

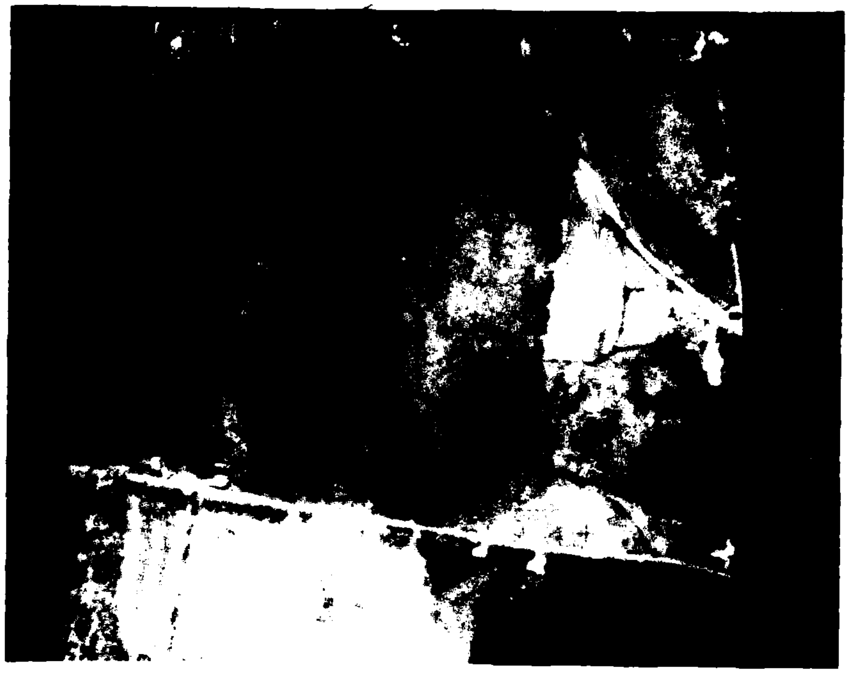

Figure 32. Scene D of block 8

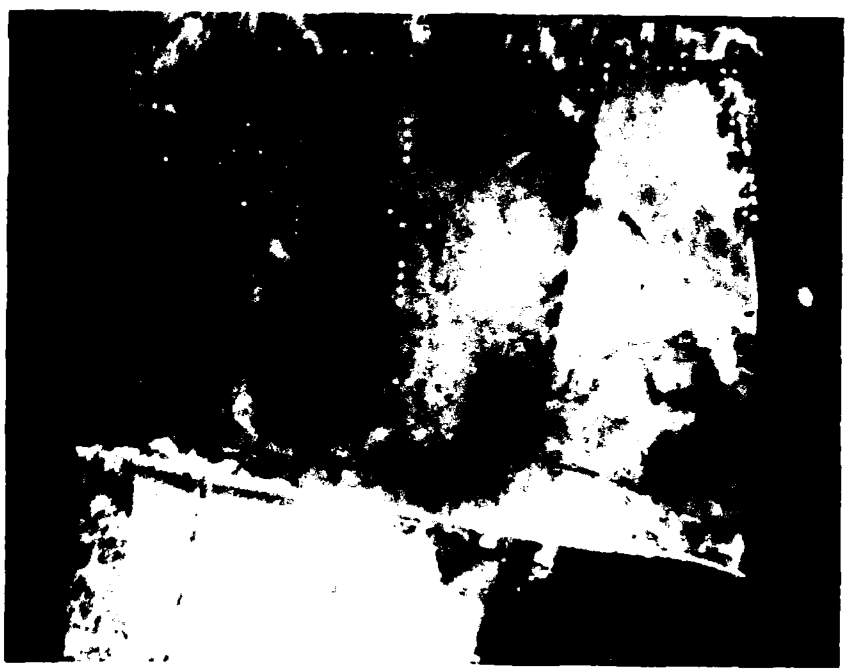

Figure 33. Scene D of block 8 – rejects

Figure 34. Scene D of block 8—pass point rejects

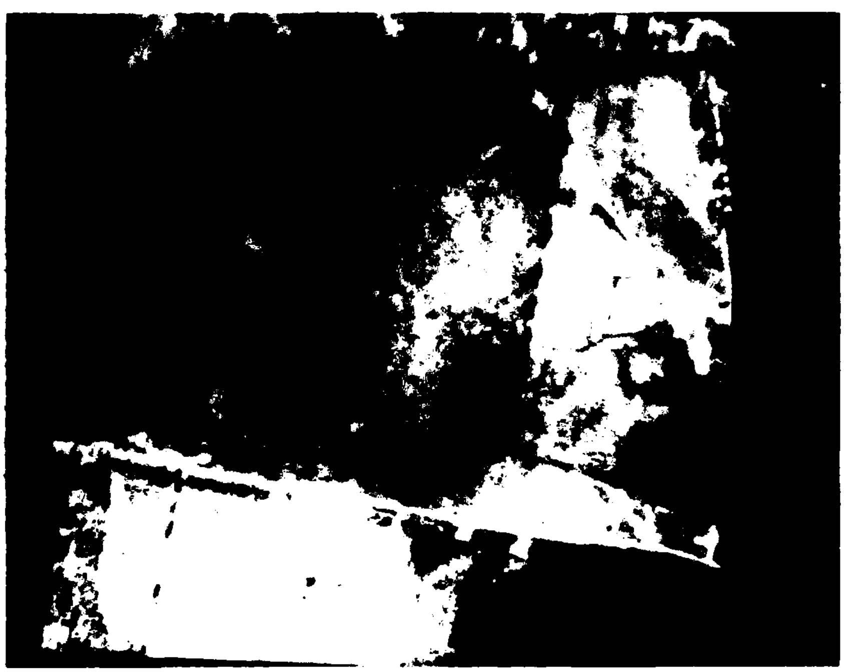

Figure 35. Scene D of block 8—pass point convergence failure

DISCUSSION

Part of the reason for the superior results from the 10 lp/mm experiment when compared to the 20 lp/mm experiment is that an experienced photogrammetrist conducted the former, whereas an analyst with little photogrammetric experience performed the latter. The analyst who performed the 20 lp/mm experiment did have extensive hands–on training on the interactive processor. Note figures 5 and 17 where the process was initiated in fields where even a skillful analyst usually has difficulty in measuring X–parallax. In cases like this, the experienced analyst would begin elsewhere or else attempt a number of matches and thoroughly check the results before allowing the system to go off on its own. Thus, part of the 10 to 1 improvement in performance must be attributed to the operator. The basic law of data processing, namely "garbage in – garbage out," imposes itself once again. There seems to be no substitute for knowledge and experience.

X–parallax measurements can be improved by tight control of Y–parallax. There should be zero Y–parallax error in output when exterior orientation is known accurately. Since the image coordinates on the master image are correct by definition, all detectable Y–parallax is applied to the slave image coordinates. This is not the case, say in UNAMACE, where the output local horizontal coordinates are correct by definition and Y–parallax error must be shared by both images. The Y–parallax correction is seen to be expressed by a simple equation involving image measurements and coefficients which are functions of the focal length and exterior orientation data[9].

Y–parallax is controlled to some extent in the DIAL X–parallax processor but not at all in the pass point processor. From table 3, it is seen that nearly 50 percent of the pass point rejects were rejected because of a large Y–parallax error– –3 lines or more. When those points and the edge rejections (format rather than procedural problems) are excluded from the mismatch presentations, the errors appear to be scattered and amenable to relaxation procedures for improvement. The 10 lp/mm results shown in figures 2, 3, and 36 also are mostly scattered, and they too should be amenable to relaxation techniques. Note that by comparing tables 1 and 3 it is seen that the pass point processor operating on X–parallax rejects recovered about 69 percent of the failed matches. If the pass point processor Y–parallax and format rejects are excluded, it is seen that the pass point processor recovered about 90 percent of the failed X–parallax processor matches. Two things should be noted. One, the "recovered" matches will not be as accurate as those derived by the X–parallax procedure. Two, the X–parallax processor struggles, and sometimes vainly, in steep areas with little signal power[10].

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[9]M. Crombie, and W. Baracat. *Applying Photogrammetry to Real Time Collection of Digital Image Data*. U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL–0275, November 1981, AD–A116 770.

[10]M. Crombie. *Errors In Automatic Pass Point Mensurations Using Digital Techniques*. U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL–0232, June 1980, AD–A087 443.

Figure 36. Lake area results from the 10 lp/mm run

Consider the lake in figure 36. The 10 lp/mm process failed here as expected. The process results would have been more impressive if the several spots in the center of the lake had failed also. Most of the lake "matches" near the shore can be explained by noting the correlation window was 15 by 15, which means the correlation function extended onto the shore. For a visual reference, note that each of the reject blobs is a 3 by 3 pixel. Forty-five points were measured along the shore line using the pass point program and the 20 lp/mm data. The average elevation was 316.4 meters and the average Y-parallax error was 15.4 m or 0.6 pixel spacing. Several points near the shore line were extracted from the 10 lp/mm DTM and their average value turned out to be 317.4 meters. Also the lake itself turned out to be rather bumpy. The "measurement" of X-parallax that is not there can be avoided simply by coordinating the process with another processor that is looking for lakes, fields, and forests. The lake and pond finder could determine boundaries to the best of its ability and those boundaries could be sharpened by the X-parallax processor. The same notion holds for urban areas. Note the urban region in figure 36. The reason there are not too many rejects over the region comes from the low frequency content of the input data. It should be noted that the correlation results from the X-parallax processor should provide excellent low frequency guidance and control to a high frequency, low pull-in match function for buildings and street edges.

CONCLUSIONS

1. Y–parallax can and should be controlled to an accuracy defined by the exterior orientation data.

2. X–parallax should be measured in rural areas with digital imagery containing no more than 10 lp/mm: resolution.

3. The X–parallax processor must be coordinated with other processors if more acceptable results are to be achieved.

4. At this time only knowledgeable analysts should be allowed to operate on X–parallax processors for production.

5. Relaxation methods should be applied to rejected matches if they are scattered over rural areas.

END

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